THE CHEMCAM INSTRUMENT FOR THE 2011 MARS SCIENCE LABORATORY MISSION: SYSTEM REQUIREMENTS AND PERFORMANCE

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ABSTRACT

The ChemCam experiment is one of ten science investigations onboard the Mars Science Laboratory (MSL) rover "Curiosity", scheduled for launch in late 2011. The instrument is a combination of a Laser-Induced Breakdown Spectrometer (LIBS) and a Remote Micro-Imager (RMI) camera. The LIBS subsystem will provide remote sensing data on the composition and elemental abundances of rocks and soils via active interrogation by a high-power laser, and passive spectra of targets using natural illumination. The RMI subsystem provides high-resolution images of the target regions interrogated by the LIBS laser, and will be used to provide geologic context for the LIBS data.

This is the first use of a LIBS system in space.

Extensive testing at the subsystem, integrated-instrument and integrated-system level show that performance requirements are met, and that ChemCam is capable of achieving its science goals when it lands on the surface of Mars in August, 2012.

1. THE MSL MISSION

The NASA's MSL rover is a large, mobile laboratory, about twice as long (about 3 meters or 10 feet) and five times as heavy as the twin Mars Exploration Rovers, Spirit and Opportunity, launched in 2003.

The overall scientific goal of the mission is to explore and quantitatively assess a local region on Mars surface as a potential habitat for life, past or present.

The MSL rover, built by Jet Propulsion Laboratory, is designed to carry ten scientific instruments and a sample acquisition, processing, and distribution system. The various payload elements will work together to detect and study targets of interest with remote and in situ measurements, to acquire samples of rock, soil, and atmosphere and analyze them in onboard analytical instruments, and to measure the local environment of the rover.

The MSL rover, now called "Curiosity", has been integrated and tested at JPL, and will be shipped to Cape Canaveral around the end of June, 2011.. Curiosity will be re-integrated there with the other flight elements (Entry, Descent and Landing system, Cruise stage) before its launch in November-December 2011. The landing site is currently in selection by NASA.

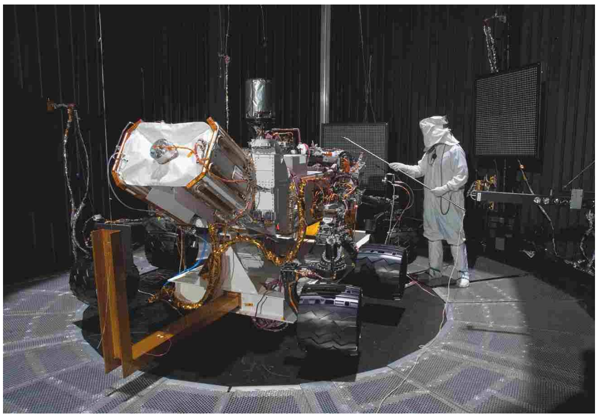

Fig. 1: Curiosity during thermal test (JPL photo)

2. CHEMCAM DESCRIPTION

The ChemCam experiment is a combination of two instruments:

- a Laser-Induced Breakdown Spectrometer (LIBS),
- a Remote Micro-Imager (RMI) camera.

The LIBS subsystem will provide remote sensing (up to ~7 m range) data on the composition and elemental abundances of rocks and soils via active interrogation by a high-power laser. It is also possible to obtain passive spectra of targets using the LIBS subsystem and natural illumination. This new technique for planetary exploration is of great interest with its remote sensing capability, including the ability to remotely remove dust or weathering coatings.

The RMI subsystem provides high-resolution images of the target regions interrogated by the LIBS laser, and will be used to provide geologic context for the LIBS data.

ChemCam is physically divided into two separate units: the Mast Unit (CCMU), and the Body Unit (CCBU).

The CCMU is located at the top of the rover mast, ~2 m above ground level, and consists of an optical telescope, a Nd/KGW laser, the RMI camera and supporting electronics. The CCMU is provided by the French part of the ChemCam team, the IRAP laboratory in Toulouse, which is supported by CNES, the French Space Agency.

The Body Unit (CCBU) consists of an optical demultiplexer, three independent spectrometers with CCD detectors, the command and data unit, and supporting electronics, and is located inside the body of the rover. The CCBU is provided by Los Alamos National Laboratory.

The CCMU and CCBU are interconnected via fiber optic and electrical cables, both contributed by Jet Propulsion Laboratory. JPL is also supplying a thermo-electric cooler (TEC), to cool the CCBU detectors.

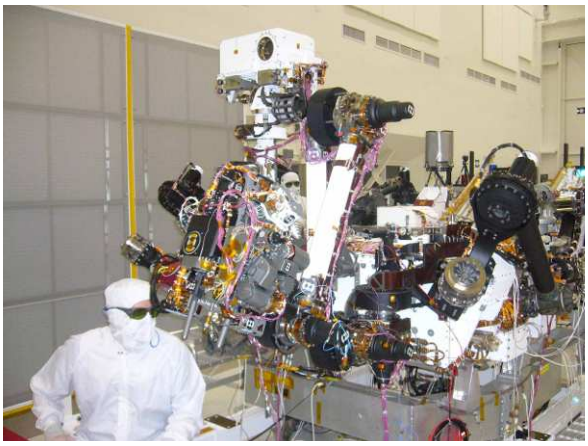

Fig. 2: building Curiosity
(CCMU at the top of the mast – JPL photo)

The LIBS technique [1] uses ~5-8 nsec and ~24 mJ laser pulses, which are focused on a target through a telescope, to ablate and electrically excite target material. Due to the high energy density on the rock, a small spot is vaporized and plasma is created. The plasma emits photons with wavelengths characteristic of the elements present in the material. Theses photons are collected by the same telescope and an optical lens system, and are then sent to the Body Unit via optical fibers. There, the optical bandwidth (240-850 nm) is split into three bands by a demultiplexer and provided to the three spectrometers.

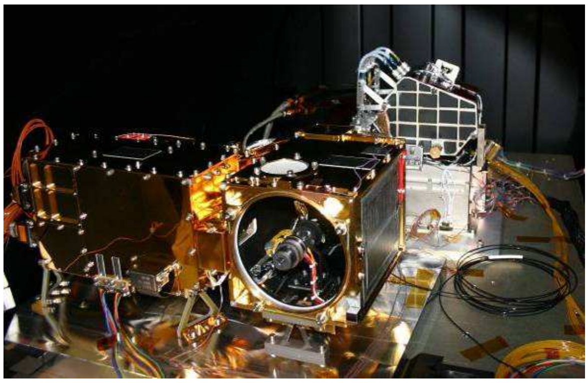

Fig. 3: ChemCam Instrument during test at LANL
(CCMU in foreground – LANL photo)

The RMI camera [2] collects a small fraction of the optical flux passing through the same telescope and images the same scene as the LIBS with high resolution.

The general schematic of the instrument is given here:

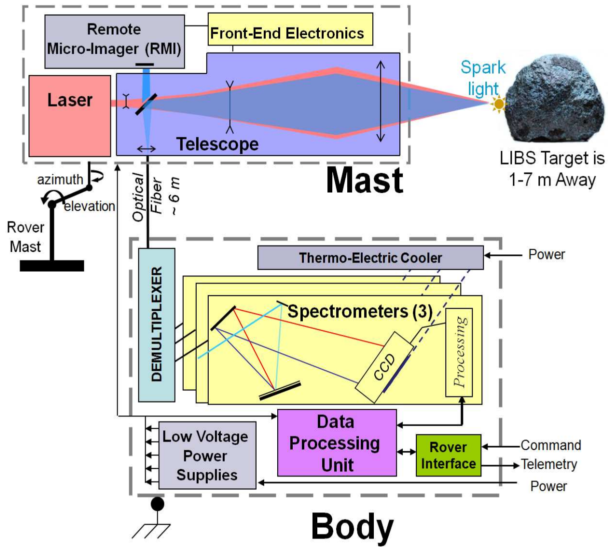

Fig. 4: Schematic of ChemCam measurement

2.1 Mast Unit Description

The Mast Unit (CCMU) (Fig. 5) consists of two boxes:

- the OBOX (Optical Box), containing the LIBS laser, the RMI camera, a 110 mm aperture telescope and the autofocus devices

-the EBOX (Electrical Box), containing all the boards necessary to provide power, control the OBOX, analyze the autofocus signal, and transmit data to Body Unit.

Fig. 5 ChemCam Mast Unit Flight Model (Cnes Photo)

The Mast Unit OBOX contains the LIBS laser source, a Galilean telescope for expanding the beam, a Cassegrain telescope (Fig. 6), an imaging lens system, the RMI camera, and the autofocus sub-system. The LIBS laser emits bursts of pulses, which are focused by the telescope's mirror to increase the optical density of the beam on the target.

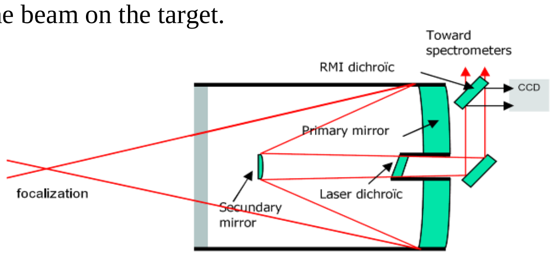

Fig. 6 Optical design of the telescope

The LIBS laser is designed with a powerful pulsed diode-pumped solid-state laser source [1] with a good quality laser beam, which has to be precisely focused on the chosen Martian rock, in order to obtain a very high energy density.

The autofocus subsystem consists of a continuous-wave laser diode, the secondary mirror translation mechanism, and electrical devices allowing modulation of the signal (to increase the signal to noise ratio) and synchronous detection of the reflected signal. The data are transmitted, in real-time, to the Body Unit which determines the range to the target, and focuses the laser beam on it.

2.2 Body Unit Description

The Body Unit (CCBU) (Fig. 7) consists of:

- the optical demultiplexer, which receives the LIBS photons from the Mast and splits the light into three broad wavelength bands, one for each spectrometer,
- three spectrometers, which spectrally disperse and detect the LIBS photons,
- the electronics box containing all the boards necessary to provide power, command the Mast and the spectrometers, receive RMI, spectral, and housekeeping data, do minimal data processing, and communicate with the rover, and
- the thermo-electric cooler (TEC), which cools the spectrometer CCD detectors.

The optical demultiplexer uses dichroic mirrors to split the wavelength ranges of a collimated light beam. The respective beams are re-imaged into bundles of 12-19 fibers of 50-70 µm diameter arranged in closest-packed circular arrangements at the demultiplexer end and linear arrays at the spectrometer end. Slits of 21-25 µm width are fastened to the end of each fiber array as the entrance aperture of each spectrometer. The spectrometers are relatively simple crossed Czerny-Turner optical designs, after the Ocean Optics HR2000 model, and use dielectric mirrors and holographic gratings (2400 lines per mm for the UV and VIS, and 600 for the VNIR) for light dispersion. The three spectrometers are mechanically identical and are stacked together into a single unit.

For detectors the ChemCam LIBS spectrometers employ e2v 42-10 back-illuminated 2048 x 512 pixel CCDs that are operated in low-noise, advanced inverted mode. Each pixel is 13.5 microns square, for an image area of 27.6 x 6.9 mm. The VNIR CCD employs a custom anti-etalon coating, while the other units use off-the-shelf coatings to optimize transmission in their respective spectral ranges. The full wells were measured at 255k, 190k, and 216k electrons for the UV, VIS, and VNIR spectrometers, respectively.

A thermo-electric cooling (TEC) system was added to the CCBU to lower the CCD temperatures to -10°C for most analyses. This system consists of an Al base plate and side shelf on which three TEC units from Marlow Industries are mounted, along with heat-conducting copper straps to each detector (Fig. 7). TEC power is controlled separately from the ChemCam instrument: it can be turned on minutes to hours prior to using ChemCam for spectroscopy. The overall system design was developed and implemented by JPL personnel in collaboration with LANL.

The Body Unit electronics consist of one low-voltage power board, one spectrometer board, and a data processing unit (DPU) board. The DPU contains a UTMC 80C196 microcontroller, which is supported by two Actel field programmable gate arrays (FPGAs). Communication with the rover and with the Mast Unit is through low voltage differential signal (LVDS), high-speed serial links.

Fig. 7: the ChemCam Body Unit Flight Model (LANL photo)

3. CHEMCAM REQUIREMENTS

3.1 General science

ChemCam addresses four of the five MSL mission objectives, including:
(1) characterize the geology of the landing region,
(2) investigate planetary processes relevant to past habitability,
(3) assess the biological potential of a target environment, and
(4) search for materials that would present toxic hazards to humans.

It will operate on its own, providing remote analysis and images, or as a strategic instrument, providing information for the team to decide analysis with other in-situ instruments.

Various analysis or investigations are requested from ChemCam:
(1) rapid remote rock identification,
(2) dust removal,
(3) soil and pebble composition surveys,
(4) quantitative analysis, incl. trace elements,
(5) depth profile,
(6) calibration,
(7) detection/characterization of water/hydration

Science Requirements for LIBS include obtaining major element abundances to ±10%, along with minor and trace element characterization (including H, Li, Be, C, N, S), some to as low as 10 ppm.

The instrument specifications (see below) are derived from the Science investigations.

3.2 System requirements

The main system requirements are presented here:

ChemCam shall be able to acquire LIBS data, at target range of 1m to 7m, and RMI data up to infinity.

The system shall provide sufficient light from the LIBS spark to support the signal/noise ratios specified for the spectrometers.

The instrument shall be able to provide a target composition depth profile > 1 mm into a rock target at distances to at least 6 m.

The laser shall be capable of providing > 3e6 shots over the period of a full Mars year, and capable of providing > 3000 shots per sol.

3.3 LIBS specifications

In order to excite small areas of geologic targets to temperatures high enough to radiate photons that can be analyzed by the LIBS subsystem, laser Energy Densities of > 10 MW/mm² at the sample are specified at distances ranging from 1.5 to 7 m from the rover mast, in a temperature range of -20 °C/+20 °C.

Other laser requirements for successful LIBS analyses include pulse energy at the sample > 13 mJ, pulse durations of 5-8 ns and, (at laser level) beam quality of $M^2 < 3$.

The ChemCam telescope must perform three distinct functions:

- it must direct and focus the intense laser output (λ=1067 nm) on targets over the required range, with a precision of +/-0.5% of the target distance,
- it must efficiently collect the photons (λ range = 240–850 nm) emitted by the plasma cloud generated at the sample by the laser and transmit (efficiency 15-40%) this light to the remotely-located spectrometers,
- it must act as specialized "telephoto" lens for the RMI subsystem. The entire optical subsystem must be capable of auto-focusing very precisely over the required operational range.

The optical demultiplexer subsystem of the BU must efficiently divide the LIBS photons collected by the telescope into three optical bands (UV = 240-340 nm, VIS = 385-465 nm and VNIR = 475-850 nm) and feed these photons to the three spectrometers that are optimized for their respective wavebands.

The spectrometers are required to achieve optical resolutions of 0.2, 0.2, and 0.65 nm (FWHM) for UV, VIS and VNIR respectively and the wavelength drift with temperature should be < 0.1 pixel/C.

3.4 RMI specifications

The RMI camera will be used to provide high-resolution images of the LIBS analysis geologic context, and also could be used, combined with other cameras products, to form mosaics.

The RMI camera itself must provide < 100 µrad resolution (with 0.2 contrast) to enable adequate imaging of the interrogated samples, from 1 m to infinity. That will allow to discriminate a 1 mm spot at 10m.

Field of view must be higher than 15 mrad (0.15m at 10m).

RMI will benefit from the auto-focusing capability of the telescope, and will be able to optimize exposure time with an on-board auto-exposure capability.

4. MEASURED PERFORMANCES

Several series of tests have been done at the sub-system (CCMU or CCBU level), the ChemCam level at LANL, and also the Rover level at JPL, including tests in a Martian environment, exploring the range of expected temperatures. The 2-year delay of the MSL launch (from 2009 to 2011) has been used for a number of additional ChemCam performance tests.

4.1 LIBS performances

a. Laser and telescope (Mast Unit)

The energy has been measured at its best value at cold (-10 °C) temperature [3], as intended by the design which is adapted to the Martian environment. At this temperature it meets its requirement (Fig. 8).

The pulse duration has been measured at 5ns, also conforting the laser-alone measurements.

The beam shape and the concentration of energy on the target have been first simulated with ASAP software, predicting 600 µm at 7 m (95% of energy). Tests results are slightly better due to a good beam quality at laser level (M²) and a well aligned optical system (Fig. 9 & 10).

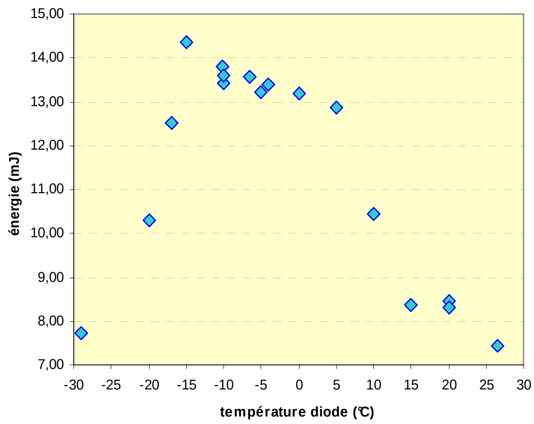

Fig. 8: Energy versus laser temperature.

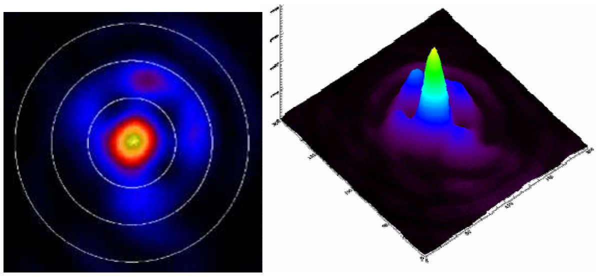

Fig. 9 : Concentration of energy measured on the target at 9 m

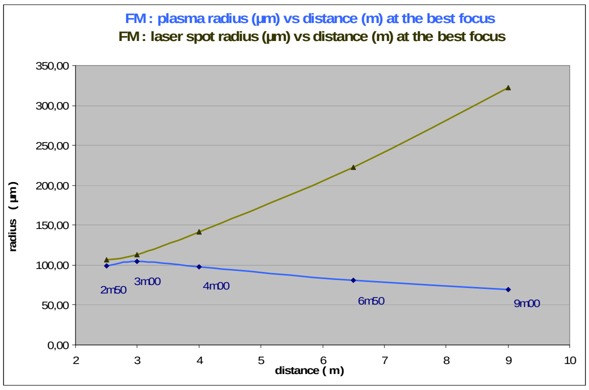

Fig. 10 : Radius of the laser spot versus distance at the best focus.

The LIBS Energy Density (ED) is computed from the laser beam shape around the best focus, and plotted versus $1/d^2$ (Fig. 11), “d” is the distance to target at the best focus.

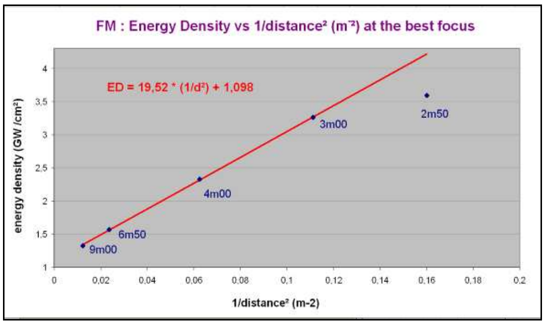

Fig. 11: Energy Density deposited on the target versus 1/distance².

Results show that:

- at cold temperature, with laser diodes around -10 deg C, the LIBS laser provides the highest energy, the quality plasma is at its best, and the Energy Density requirement is fully respected, with margin.
- at ambient temperature, and short distances, the Energy Density could be up to 3.5 MW/mm², but is limited by the spot size which could not be smaller than 200 µm diameter (fig. 10), while concentrating the most energy inside,
- at ambient temperature, and long distances, the ED is still compliant with the requirement, but, above 7m, the creation of plasma is very depending on the interaction between the laser beam and the rock.

The LIBS depth of field (DoF) is computed with a criteria of 20% of loss of ED from the maximum value. Performance is constant between 2.5 m to 9 m (Fig.12), giving a ½ DoF of about 11 steps of the motor.

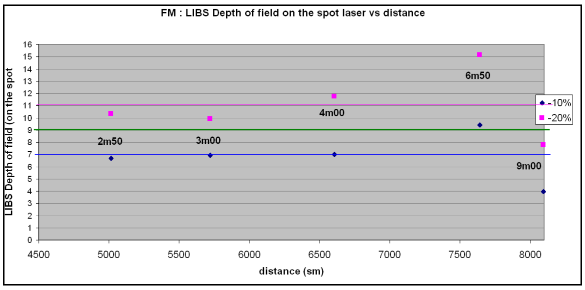

Fig. 12: ½ LIBS DoF (motor steps) versus target distance given by Laser ED criteria

This is validated by the spectral analysis of the response of the spectrometers on the three UV, VIS and VNIR spectral bands: a loss ratio criteria of 20% gives ½ DoF constant of 15 steps (Fig. 13) whatever the distance.

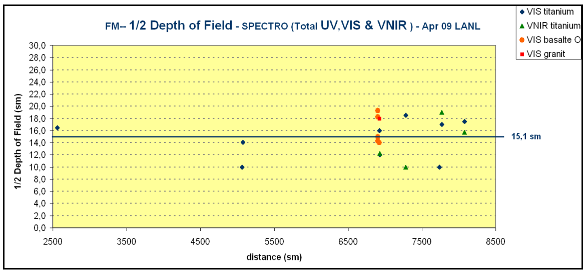

Fig. 13 : ½ LIBS DoF versus motor position given by spectrum criteria

In addition to the Autofocus computation, an offset, specific to the LIBS, is added in order to go to the best LIBS focus on the target. The LIBS offset law has been determined using the spectrometers, and depends on the distance.

The precision of the autofocus is +/- 8 steps, 1-sigma, which is lower than the LIBS 1/2 DoF. So, the focusing performance is obtained with margin [4].

b. Fiber Optic Cable, Demutiplexer and Spectrometers (Body Unit)

The MU and the BU are connected by a JPL-provided, six-meter long fiber optic cable that transmits LIBS photons from the Telescope to the Spectrometers. Fig. 14 shows the required and desired transmission values and the final measured performance of the fully assembled cable.

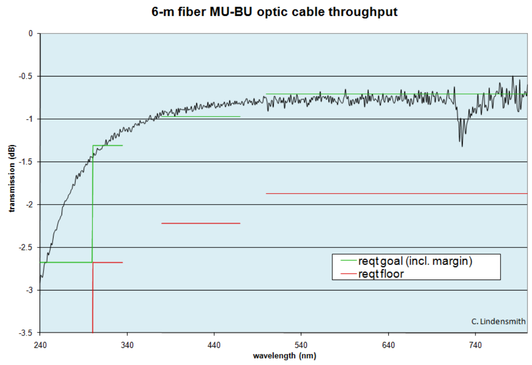

Fig. 14: Requirements and Performance of the BU to MU Fiber Optic Cable

It can be seen that the cable fully meets all transmission requirements and closely approaches or exceeds the design goal over the full wavelength range.

CCD detector noise is an important component of the overall signal-to-noise ratio of the system and considerable effort was expended to reduce the noise level as much as possible. This included the incorporation of the thermoelectric cooler (TEC) into the Spectrometer detector subsystem to reduce the CCD thermal noise component as much as practical. Fig. 15 shows the dark current level, for each of the three Spectrometers, that is achieved at 0 deg C, which will be a typical temperature for data acquisition on Mars. These levels are slightly different for the three spectrometers due to the individual electronic gain settings. What should be noted however, is the very low noise levels for each of the detectors, as indicated by the standard deviations given in the plot. It can be seen that all noise levels are ≤ 1 digital count, which is very far below the anticipated number of counts that will be obtained during LIBS data acquisition.

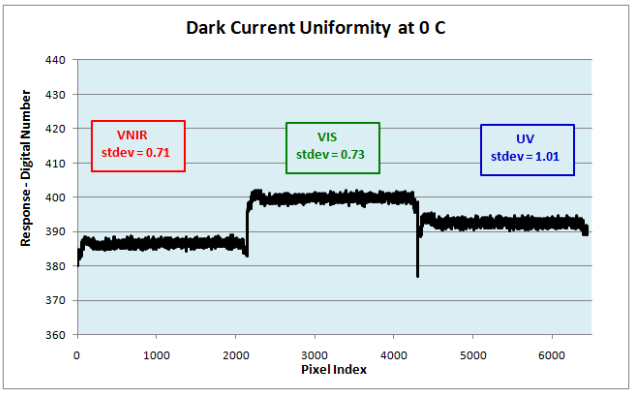

Fig. 15: Spectrometer CCD Noise Levels

High spectral resolution is needed in the Spectrometers in order to be able to separate and identify the many elemental emission lines encountered when using the LIBS technique. The resolution required to meet the elemental accuracy goals for the experiment are 3.0, 5.0 and 4.3 pixels FWHM for the VNIR, VIS and UV spectrometers respectively.

Inspection of Fig. 16 to 18 shows that the resolution requirements are met in each of the three spectrometers. Additionally, the Fig. 19 shows variation in the VNIR and VIS spectral resolution across the full survival temperature range for the CCBU during the mission. It can be noted that there is considerable margin in the performance across a wide temperature range except for the VNIR spectrometer at the very coldest temperature where the requirement is slightly exceeded. It is not anticipated that the CCBU will ever be operated at this temperature.

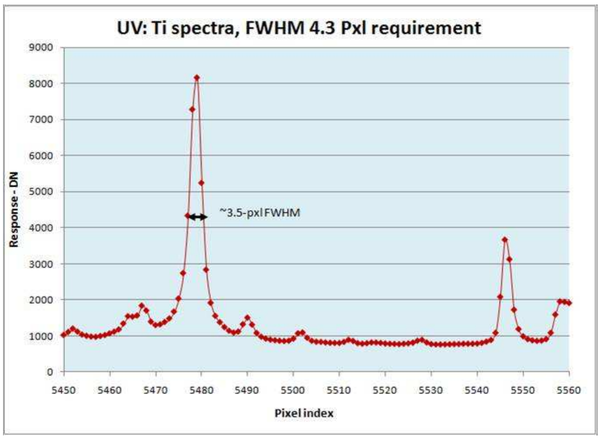

Fig. 16: UV Spectrometer Resolution

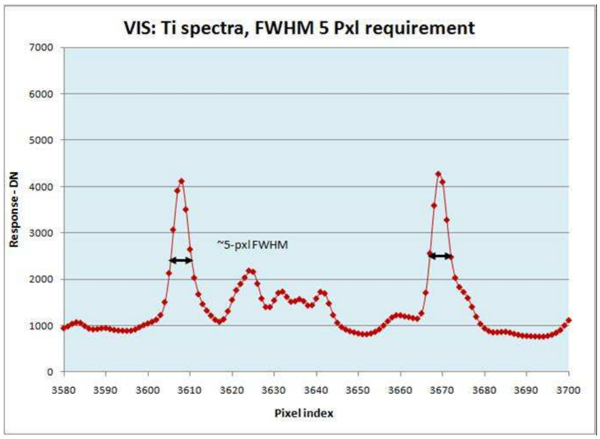

Fig. 17: VIS Spectrometer Resolution

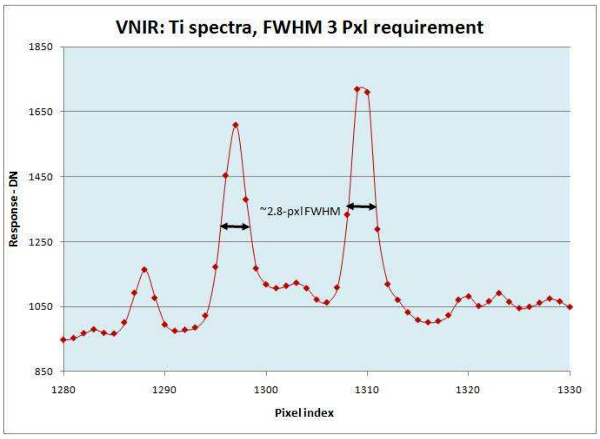

Fig. 18: VNIR Spectrometer Resolution

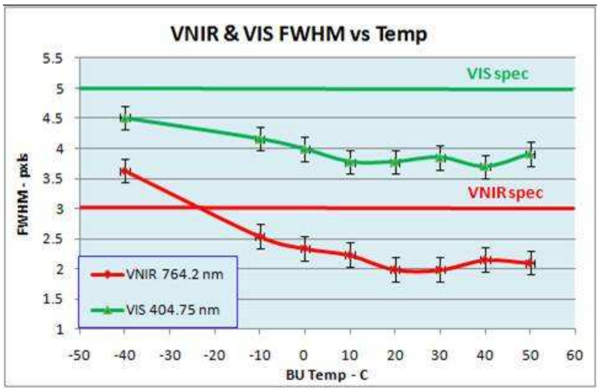

Fig. 19: Spectrometers Resolution versus Temperature

As the Spectrometers must operate over a fairly large temperature range, it is important that measured photon wavelengths do not shift significantly across the detector as temperature varies. For CCBU, the total drift for a given wavelength over the operating temperature range (-40 to +50 deg C) was limited to 6 pixel. Fig. 20 shows the measured wavelength shift over the pertinent temperature range for all three Spectrometers and all three drifts are well within spec, indicating a stable optical system over temperature.

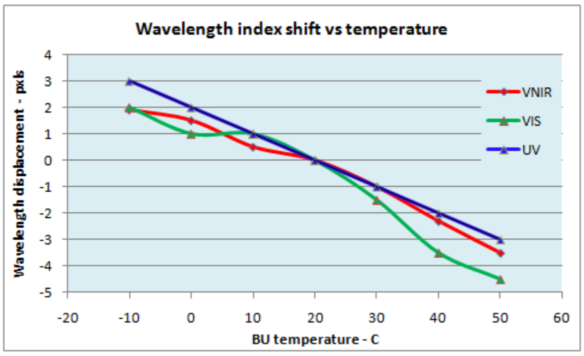

Fig. 20: Spectrometers wavelengh shift

In addition to operating in the normal 1-D spectral data acquisition mode that is typically used for obtaining LIBS spectra, the CCD detectors can also be operated in 2-D mode, where an image of the projected light spectrum can be acquired and downlinked to the Earth (see Section 4.3).

c. Integrated-instrument LIBS performance

Probably the most important performance criteria that needs to be met for the fully-integrated ChemCam instrument is the overall system gain, as the gain is critical to being able to meet the elemental abundance accuracy requirements that enable good science at Mars. The integrated instrument gain has been measured and the gain for the VNIR channel is shown in Fig. 21.

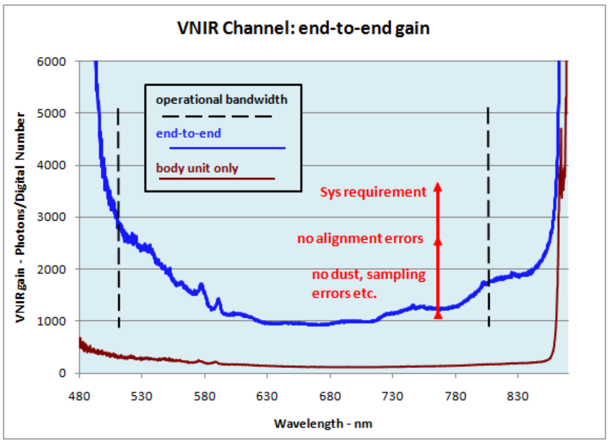

Fig. 21: End-to-End Gain for VNIR Channel

It is important to note that lower gain values correspond to “higher sensitivity”, i.e. fewer photons are required to generate a single spectrometer count. It can be seen that the CCBU-only gain is very low, as indicated by the gain line lying along the bottom of the plot. When the CCMU and the Fiber Optic Cable are integrated with the CCBU, the gain is somewhat increased, due to photon losses, etc. in the system, but still far exceeds the system requirement, which is indicated by the top triangle lying on the vertical red line. The measured gain closely approaches the theoretical maximum performance of such a system, which is shown by the lower triangle on the red line. It can be seen that integrated-system performance is very good compared to requirements over the entire VNIR wavelength range and similar results have been obtained for both the VIS and UV wavebands.

However, for LIBS end-to-end performance, the plasma creation must be considered as well. The overall performance will be described in Section 4.3.

4.2 RMI performances

The RMI camera is a flight spare from the ROSETTA European space mission to a comet. Performances at CCD and camera level are known from this program, and the camera has flight heritage.

For ChemCam, tests have been done at IRAP, on the RMI camera alone, then integrated on CCMU [5].

The Field-of-view has been measured at 20 mrad, independent of the distance, meeting the requirement of > 15 mrad.

The Resolution, measured with a USAF-type target, is slightly different in the vertical and horizontal directions due to astigmatism. The object separation, at 0.2 contrast is 78 – 85 µrad in the vertical direction, and 87 -105 µrad in the horizontal (Fig. 22).

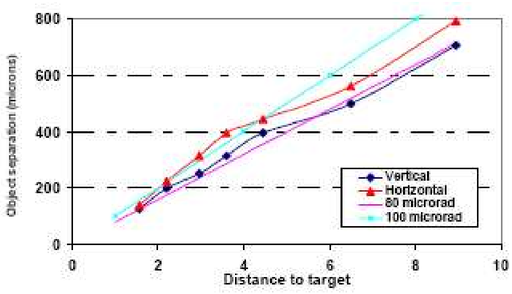

Fig. 22: The RMI camera resolution

The vertical resolution is equal to the highest resolution of all cameras on board Curiosity.

Wavelength response is calculated from elemental measurements (CCD QE, lenses and dichroics measurements). The RMI camera will collect light from 0.4 to 0.9 µm. Note than only 8% to 18% of the light coming into the telescope end up in the RMI so impact to the LIBS performance is minimal.

Various idiosyncrasies of the RMI camera have been characterized (flat field, ghost, dark, smearing, co-alignment, distorsion, etc…). They have been taken into account to generate correction algorithms, which will be applied to images to improve their quality [5].

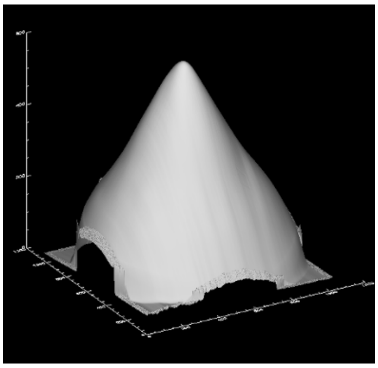

Fig. 23: The RMI camera Flat-Field in 3D

A typical RMI image of a Banded-Iron rock is shown here:

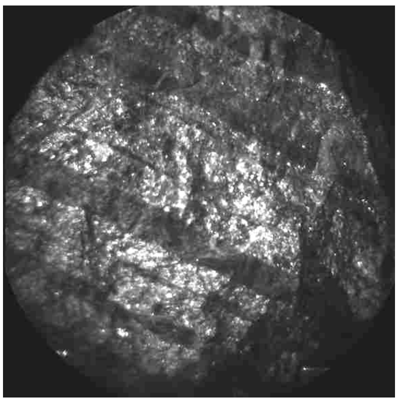

Fig. 24: Banded-Iron RMI image

4.3 Integrated-system performances (at Rover level)

ChemCam is considered fully integrated only at Rover level, when optic fiber and the Mast unit cover (RWEB) are installed. So, tests have been done at Rover level, not only for verifying functionalities, but also performances. Of course, for practical reasons, tests at Rover level are very time-restricted, and only a subset of the performances have been checked, first at ambient, during two slots of tests, then during the Rover Thermal Test . This last test has been the only opportunity for us to test ChemCam end-to-end in thermal and optical fully representative conditions. The results have confirmed the performances measured before, showing very good spectra and images.

a. LIBS:

Laser energy and pulse duration have been verified, and showed no degradation.

End-to-end gains have been measured (see Section 4.1-c). They showed no degradation and confirmed the good integration of the Fiber Optic and RWEB.

2-D spectra are used for diagnostic purposes and can show any optical drifts over time or temperature as well as "hot" pixels or other flaws in the detectors. The three 2-D spectra below (Fig. 25) were obtained after all environmental testing was completed at the Rover level and show that there had been no significant changes in the optical system since prior to delivery to the flight system almost a year earlier.

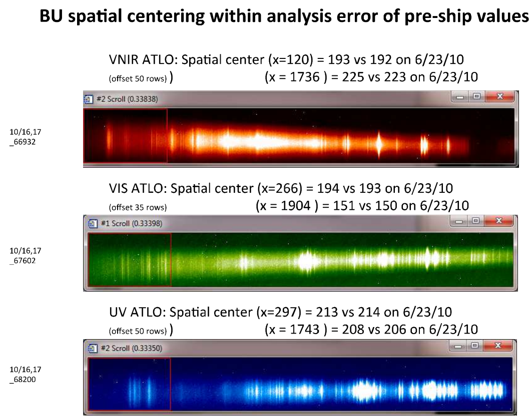

Fig. 25: 2-D Spectra Examples

Many LIBS Spectra have been acquired during Rover Thermal Vacuum and present very high quality displaying emission lines of many elements.

See hereafter an example of a quicklook spectral data product acquired during Rover Thermal test.

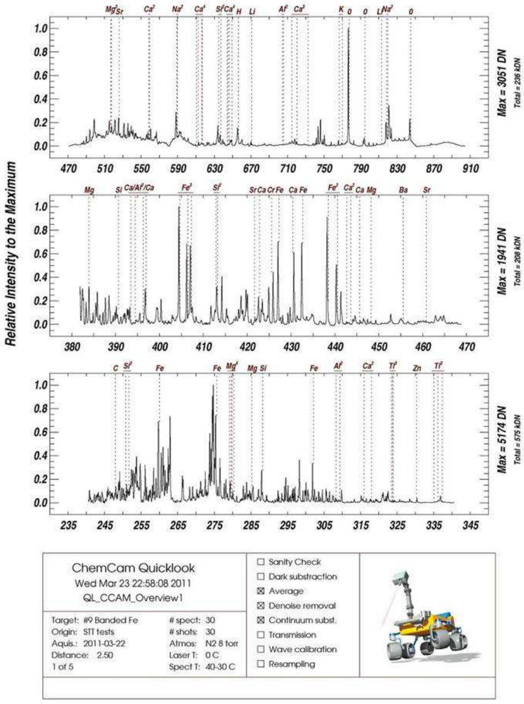

Fig. 26: Banded-Iron Quicklook spectrum

b. RMI:

A generic use of the RMI camera is to take images before and after the LIBS firing. Substracting the images shows the impact.

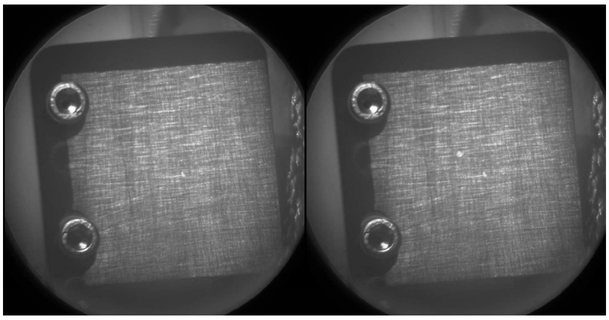

Fig. 27: RMI images of Titanium Calibration Target (before and after firing)

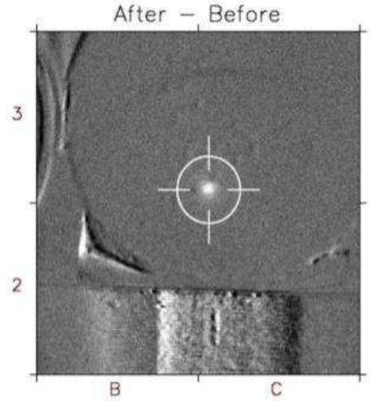

Fig. 28: Processed RMI images (after – before)

5. CALIBRATION

Calibrations tests [6] have been carried out to assess the capability of the Instrument to obtain major element abundances with a precision of ±10%, along with minor and trace element characterization.

These tests have been done, before delivery, in two configurations: with optimal laser energy during instrument thermal testing (laser = -10°C), and with degraded laser energy at room temperature. In both cases, samples were placed in a chamber with an ambient Mars pressure (7 Torr) of CO2. A limited number of standards (20) have been tested at cold, using various distances from 1.5m to 7m, and 69 standards have been tested at ambient. Also, depth profile [7], soil and dust removal have been characterized at ambient.

The accuracies of abundance prediction is checked using multi-variable analysis, and sample classification techniques. Results are available in [6].

The last opportunity for calibration has been the Rover Thermal Test in March 2011 at JPL, where MER standards have been fired with ChemCam, at 3m and 5m. Also, the on-board ChemCam calibration targets (CCCT) spectra have been acquired during this test; these CCCT will be available on Mars, for in-flight calibration.

Fig. 29: The on-board Calibration Targets (CCCT)

6. CONCLUSION

The two-years delay of the MSL launch has allowed us to fully characterize the performances of the ChemCam Instrument. Also, several hardware and software modifications have been done to improve these performances.

Now, ChemCam presents excellent performances, meeting its requirements, and is fully operational for science on Mars.

The ChemCam team is looking forward to providing remote analysis of the Martian rocks and soil!

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